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On the relationship between very low frequency North Pacific SSTA and global climate variations

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1. Introduction

It is known that the Pacific Ocean has a rich spectrum of interannual to interdecadal climate variability [Nitta and Yamada 1989; Trenberth 1990; Alexander 1992; Graham 1994; Miller et al. 1994; Lau and Nath 1994; Mantua et al., 1997; Nakamura et al. 1997, Giese and Carton, 1999, Garreaud and Battisti, 1999; Yeh and Kirtman, 2003a]. There are also indications that Pacific Ocean variability is an important component of global climate variations showing clear decadal and interdecdal variability [Graham, 1995; Lau and Weng, 1999].

Among the many manifestations of Pacific decadal variability, a climate shift in the Pacific Ocean around the mid-1970s has been extensively documented in observations [Deser at al., 1996; Mantua et al., 1997; Nakamura et al., 1997] and in modeling studies [Graham, 1994, Trenberth and Hurrell, 1994]. Recently, based on a complex statistical method (i.e., a rotated empirical orthogonal function) some authors identified multidecadal North Pacific sea surface temperature (SST) variability, which did not seem to be connected to the mid-1970s shift [Mestas-Nuñez and Enfield, 1999, Barlow et al., 2001]. Barlow et al. [2001] referred to this latter multidecadal North Pacific SST variability as the 'North Pacific mode' because its spatial structure was confined to the North Pacific in contrast to the Pacific decadal oscillation which extends throughout much of the basin. The North Pacific mode is quite vigorous in summer in contrast to the Pacific decadal oscillation which peaks during October-March [Mantua et al., 1997; Zhang et al. 1998; Barlow et al., 2001]. Barlow et al. [2001] argued that the North Pacific mode has distinct correlations with precipitations over the US that differs from the Pacific decadal oscillation.

Moreover, recent observational studies have suggested that Pacific decadal variability may consist of more than one particular mode [Minobe 1997; Enfield and Mestas-Nuñez 1999]. Wu et al. [2003] suggested that Pacific decadal variability is composed of two distinct modes, i.e., a decadal to bidecadal tropical Pacific mode and a multidecadal North Pacific mode. They argued that the tropical Pacific mode originates predominantly from local coupled ocean-atmosphere interaction within the tropical Pacific, and that the North Pacific mode originates from local atmospheric stochastic processes and coupled ocean-atmosphere interaction. These recent studies indicate that the multidecadal North Pacific SST variability is distinct from the classical Pacific decadal oscillation in terms of spatial structure, timescales and forcing mechanism. In this paper we explore the characteristics of multidecadal SST variability in the North Pacific along with its relationship to global climate variations both using observations and a coupled general circulation model (CGCM) simulation.

We do not rely on complex statistical methods and have not made an attempt to explain the physical mechanism that drives this variability. Rather, we merely document its spatial-temporal characteristics and how this variability may connect to climate variations. Our result suggests that multidecadal North Pacific SST variability, which is different from the classical Pacific decadal oscillation, is dominated by much longer timescales with a confined structure in the western North Pacific. The model results suggest that the multidecadal SST variability in the North

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Pacific appears to be independent of tropical variability, however, it is associated climate variations in the extratropics of both Hemispheres.

2. Data and Model

We used monthly mean observed SST data taken from January 1950 to December 2000 which were analyzed by the National Centers for Environmental Prediction [NCEP; Reynolds and Smith, 1994]. This dataset has values at ocean points on a 2° latitude-longitude grid.

The atmospheric component of coupled model is the Center for Ocean-Land-Atmosphere Studies (COLA) atmosphere general circulation model (AGCM) with triangular truncation at wave number 42 and 18 vertical levels. The ocean model is adapted from the Geophysical Fluid Dynamics Laboratory (GFDL) modular ocean model [Rosati and Miyakoda, 1988; Pacanowski et al., 1993] version 3 (MOM3). The model's spatial domain is global in longitude and extends from 75°S to 65°N in latitude. The grid has 240 uniformly spaced points in longitude. There are 134 points in latitude with higher resolution near the equator expanding to a maximum of 0.5° resolution at 11°N.

The component models are anomaly coupled in terms of heat, momentum and fresh water [Kirtman et al., 2002]. The atmospheric initial states are taken from a 30 year simulation with observed SST. Similarly, the ocean initial state is taken from a 30 year simulation with climatological surface fluxes. The coupling frequency of the model is once a day with daily mean values being exchanged between the ocean and the atmosphere. The simulation has been run more than 200 years and all of the analysis shown here is based on the data for the last 200 years.

3. Results

A prominent feature of the Pacific decadal oscillation is known as the mid-1970s climate shift [Deser et al., 1996; Guilderson and Schrag, 1998]. The SST after this shift, relative to the prior period, was cooler in the central North Pacific around 30°N and warmer in the tropical Pacific basin [e.g., Graham 1994; Trenberth and Hurrell 1994, Wang, 1995]. Figures 1a-c show the first empirical orthogonal function (EOF) of SST in the Pacific Ocean (Fig. 1a) and the time series of the principal component (PC) (Fig. 1b) and that of a 10-year running mean (Fig. 1c) for the period of 1950-2000.

The spatial structure of the first EOF is dominated by the usual ENSO signal in the tropical Pacific, with the PC time series showing predominantly interannual variability (Fig. 1b). The spatial structure of the SST variability in the North Pacific, which is associated with tropical cold anomalies, is characterized by warm western and central North Pacific with an elliptical shape and anomalies of the opposite sign to the east, north and south [Weare et al., 1976; Alexander, 1992; Deser and Blackmon, 1995, Lau and Nath, 1996, Alexander et al., 2002].

The smoothed PC variation (Fig. 1c), which is indicative of the Pacific decadal oscillation, shows a very sharp transition from a multiyear warm state in the mid-1970s to a cold state which persists through 1995. The Pacific was known to undergo a climate "regime shift" around the mid-1970s. Perhaps, one of the most well known hypotheses for the Pacific decadal oscillation is based on the idea that the decadal variability of the tropical ocean-atmosphere coupled system forces changes in the midlatitude Pacific through an atmospheric bridge or tropical-extratropical teleconnections in the ocean and atmosphere [Trenberth 1990; Graham, 1994; Gu and Philander 1997; Kleeman et al. 1999].

On the other hand, if we focus on the band of strong SST anomaly (SSTA) variance, which is centered near 40°N, stretches from the coast of Asia into the date line (Fig. 1d), we find that the "regime shift" is much more gradual. Fig. 1e shows the time series of SSTA averaged over 35°N~45°N, 130°E~170°E, corresponding to the region of largest variance. The 10-year running mean applied to the same time series is shown in Fig. 1f. The standard deviation for the time series shown in Fig. 1e is 0.68°C and the maximum SSTA for the smoothed anomalies is on the order of 0.5°C.

Contrasting the time series of Pacific decadal oscillation, the smoothed time series shown in Fig. 1f indicates a cooling trend from 1950 through 1985 with a more rapid warming beginning in the late 1980's and persisting until the present day. It does not show a transition in the mid-1970s compared to the Pacific decadal oscillation and has mostly negative phase in the period of 1960-1995 (Fig. 1f). The warming trend from 1985 to the present shown in Fig. 1f is not detected in the Pacific decadal oscillation (Fig. 1c). In contrast to the Pacific decadal oscillation, this low-frequency North Pacific SSTA variability (hereafter, referred as North Pacific mode) shown in Fig. 1f suggests variability that seems to be independent of the mid-1970s climate shift or direct tropical-extratropical teleconnections.

In order to examine the relationship between the North Pacific mode and tropical Pacific SST, we first calculated the simultaneous correlation between the tropical Pacific SST and the time series of the Pacific decadal oscillation shown in Fig. 1c (Fig. 2a). Note that shading indicates regions exceeding 95% significance. As expected, the spatial structure is quite similar to that of dominant tropical decadal SST variability showing a broad meridional structure in the eastern Pacific and extending along much of the North and South American coasts in the eastern part of the tropical basin with a triangular shape [Zhang et al., 1997, Nakamura et al., 1997; Knutson and Manabe, 1998; Giese and Carton, 1999, Yeh and Kirtman, 2003a].

Figure 2b is the same as in Fig. 2a except the correlation is computed with the time series of the North Pacific mode (Fig. 1f). In contrast to Fig. 2a, the spatial structure shown in Fig. 2b is more trapped in both the eastern tropical Pacific and subtropical Pacific. The correlation is positive in the central Pacific and negative in the eastern Pacific. The North Pacific mode has a considerable weaker contemporaneous relationship with tropical decadal variability compared to the Pacific decadal oscillation. This suggests that the decadal variability in the North Pacific Ocean may consist of more than one mode variability. One is the Pacific decadal oscillation which has a strong tropical connection and the North Pacific mode which does not appear to have much of a contemporaneous relationship with tropical variability.

To clarify the North Pacific mode further, we show the SSTA variability in a long (200 years) simulation of a CGCM. The structure of total SSTA variance for the period of 200 years in the model is presented in Fig. 3a. The spatial structure for total SSTA variance in the North Pacific has similarities and differences with observations. For example, the simulated SSTA variance in the North Pacific has two centers of action. The band of strong SSTA variance, which is centered near 40°N~45°N, stretches from the coast of Asia into the central North Pacific (140°E~170°E) (Fig. 3a). This particular feature seems to be in good agreement with observations. The other center of action is oriented to the northeast-southwest in the central North Pacific, which is associated with the variability of subtropical gyre in the model [Yeh and Kirtman, 2003b] and has some marked differences from observations. In particular, it has too much of a northeast-southwest tilt and is situated too far to the southeast.

As with the observation, Figs. 3b,c show the temporal time series of North Pacific mode, which is averaged SSTA over the region 39°N-49°N, 140°E-170°E, based on the maximum SSTA variance, for the raw data (Fig. 3b) and when a 10-yr running mean has been applied (Fig. 3c). The standard deviation for the time series shown in Fig. 3b,c is 0.65°C and 0.26°C, respectively. Maximum anomalies of smoothed SSTA are on the order of 0.6°C. The simulated SSTA variability in this region is irregular, has a rich spectrum, but also exhibits robust multidecadal variability. The power spectral analysis (not shown) of both these two time series shown in Figs. 3b,c shows significant spectral density on decadal-to-multidecadal timescales but with no preferred timescale.

The North Pacific mode simulated by the model (Fig. 3) has a longer timescale than the decadal variability in the North Pacific diagnosed from several previous studies. For example, Barnett et al. [1999] found a coupled mode of the ocean-atmosphere system, characterized by a significant power spectra peak near 20 years in the region of the midlatitude North Pacific and Kuroshio extension. Robertson [1996] suggested that the SST spectrum had a significant peak with an 18 year period in the ocean-atmosphere system of the North Pacific. Based on a linear theory in the North Pacific ocean-atmosphere system, Jin [1997] argued that coupled dynamics produce a basin-scale interdecadal oscillatory mode around 20 years within a realistic parameter regime. In contrast to the localized North Pacific mode shown in Fig. 3a, a common feature of these other proposed mechanisms is that they have a preferred timescales and are typically based on an oscillatory mode, which may be damped or self sustained and which appears to involve basin-scale coupled ocean-atmosphere interactions.

Generally, studies into the causes of midlatitude decadal variability often focus on two fundamental questions, i.e., whether decadal variability in the midlatitudes involves a coupled ocean-atmosphere mode [Latif and Barnett, 1994] or the effects of stochastic forcing on the midlatitude oceans [Hasselmann, 1976; Frankignoul and Hasselmann, 1977; Barsugli and Battisti, 1998]. We speculate that the North Pacific mode is not a coupled ocean-atmosphere mode primarily because it has no preferred timescales. Although Wu et al. [2003] defined the North Pacific mode differently than we have, they suggested that the origin of the North Pacific mode is due to the atmospheric stochastic forcing.

Figure 4 shows that the coupled model North Pacific mode is different from the coupled model's version of the Pacific decadal oscillation. Figure 4a is the first EOF mode in the Pacific Ocean for the period of 200 years and Fig. 4b is a 10-year running mean of PC time series. Similar to the observation, the tropical Pacific is dominated by the ENSO signal although it is too narrowly confined to the central equatorial Pacific. The spatial manifestations of SST variability in the North Pacific, which is associated with the tropical SST, is characterized by a northeast-southwest tilt in the central North Pacific with very little structure in the western North Pacific. Comparing Fig. 3a and Fig. 4a, it appears that much of the variability in the North Pacific mode is independent of the variability in the tropics.

However, this does not necessary exclude a connection between the North Pacific mode and the Pacific decadal oscillation in the model. The smoothed PC variations (Fig. 4b) show fairly sharp transitions from a multiyear warm (cold) state to cold (warm) state around model years 2080, 2120, 2155, 2175, 2220 and 2255. Some of these transitions are coincident to those of North Pacific mode, i.e., around model years 2160, 2230 and others are not. For example, the North Pacific mode is in a prolonged cold state during years 2100-2150 and 2230-2270 (Fig. 3c), the Pacific decadal oscillation experiences a sharp transition from a warm (cold) to cold (warm) state in the tropical (North) Pacific around model years 2120 and 2255 (Fig. 4b). The overall variability of North Pacific mode has even longer and persistent timescales than that of Pacific decadal oscillation in the model.

4. Relationship between the North Pacific mode and global climate variations.

There is considerable evidence for notable impacts of North Pacific SST with significant teleconnections spanning both the tropical and extratropical Pacific [Tanimoto et al., 1993; Zhang et al., 1998; Enfield and Metas-Nuñez 1999, Bond and Harrison, 2000; Barlow, 2001]. These recent studies have suggested that the state of the midlatitude Pacific Ocean is more fundamentally associated to climate variations than has been previously thought. Recently, Hoerling et al. [2001] argued that large scale tropospheric warming of the Northern and Southern Hemispheric extratropics occurred during the period 1998-2000, which is due to the global SST forcing. However, they suggested that the atmospheric state during this time was unrelated to the strong and protracted La Niña of the east equatorial Pacific Ocean.

Figure 5 shows the anomalous SSTA averaged during the period 1998-2000, which accompanies maximum positive SSTA in the region 35°N~45°N, 130°E~170°E and negative SSTA in the tropical Pacific. Since the tropical eastern

Pacific is relatively cold, Hoerling et al. [2001] suggested that the recent global warming during 1998-2000 must be due to some other processes or forcing. In fact, given that the tropical Pacific can have a large influence on global temperatures [Graham, 1995; Schneider et al., 1997; Bratcher and Giese, 2002], this recent warming is particularly perplexing. Hoerling et al. [2001] argued that the warming is due to the warming of Indo-Pacific warm pool.

Here we show evidence that the North Pacific mode is associated with global mean surface temperature variations in the model. Figures 6a,b show the time series of annual global mean surface temperatures (bar) with a 10-yr running mean (solid) (Fig. 6a) and the 10-yr running mean of North Pacific mode (Fig. 6b) during for the 200 years of the model simulation. Note that the amplitude of the running mean global mean surface temperature is indicated on the right of panel in Fig. 6a. The global mean surface temperature simulated in the model shows a similar relationship with variations of North Pacific mode. Both time series, i.e., solid lines shown in Figs. 6a,b, are significantly correlated with correlation coefficient 0.62 exceeding the 95% confidence.

The global mean surface temperature has a positive tendency before model year 2100 and mostly negative in the model period 2100~2150. Around model year 2150, global mean surface temperature shows a significant phase change from negative to positive. A sharp decrease of global mean surface temperature occurs in the model period 2240~2260. The North Pacific mode also shows a significant phase change from positive to negative around model years 2080~2100 and vice versa in model years 2140~2160. Similar to the sharp decrease of global average temperature, the North Pacific mode also shows a significant phase change from positive to negative around model years 2240~2260. Note that the variations of global mean land temperature (not shown) are also very similar to Fig. 6a. This result suggests that there is a connection between the North Pacific mode and the global mean surface temperature variations. We have not tried to determine any cause and effect relationship. We have only shown that the North Pacific mode and global mean surface temperature vary in phase on multidecadal timescales.

To examine the connection between the North Pacific mode and global climate variations further, Figure 7 shows the simultaneous linear regression coefficients between the 10-yr running mean time series of North Pacific mode (Fig. 3c) and other variables in the model, i.e., mean surface pressure (a), geopotential height anomalies at 850hp (b), 500hPa (c), 300hPa (d), temperature at 500hPa (e), and zonal and meridional wind anomalies at 850hPa (f). All six panels exhibit both a local manifestation and a remote association to the North Pacific mode. For example, the positive North Pacific mode is accompanied by anomalous high pressure over the North Pacific from surface to 300hPa (Figs. 7a-d) indicating a weak Aleutian pressure system. Both anomalous warm tropospheric temperature at 500hPa (Fig. 7e) and anomalous anti-cyclonic wind structure at 850hPa over the North Pacific (Fig. 7f) is consistent to weakening of the pressure system. There is also a remote association in the high latitudes poleward of 30 degrees in both Hemispheres. Both anomalous pressure at upper levels and temperature at 500hPa are high over both extratropics between 30~60 degrees except for the eastern North Pacific, Atlantic and Europe. However, the anomalous pressure from surface to 300hPa is low in the high latitudes poleward 60 degrees in the Northern Hemisphere.

The North Pacific mode shows little association of variability over the tropics, however, there are relatively large amplitudes in all longitudes of the extratropics both in the Northern and Southern Hemisphere. Particularly, Figure 7e indicates that the positive North Pacific mode is associated with mean tropospheric warming by accompanying a warming between 30~60 degrees latitudes with little association over the tropics. This primarily extratropical response is consistent with the results reported in Hoerling et al. [2001] result.

5. Concluding Remarks

Attempting to understand the natural climate variability on interannual to century timescales is an important avenue of investigation because of the need for both short-term climate prediction and credible long-term projections of global climate change. Here the North Pacific mode is described in both observations and a coupled model. The North Pacific mode from the model simulation has some common characteristics with the observations. First, the two time series shown in Fig. 1e and Fig. 3b are based on maximum SSTA variance confined to the western North Pacific. Second, both time series have low frequency variability, which appears to be longer than the classical Pacific decadal oscillation.

The North Pacific mode appears to be different from the classical Pacific decadal oscillation in spatial structure and dominant timescales. Our result suggests that the North Pacific mode has little association with tropical decadal variability. This is in contrast to the Pacific decadal oscillation.

Recent studies have suggested that the state of the midlatitude Pacific Ocean is fundamentally associated to the global scale climate variations. We investigated the relationship between the North Pacific mode and global climate variations in the model. We found that the North Pacific mode and global mean surface temperature vary in phase on multidecadal timescales. Moreover, the North Pacific mode shows remarkable association of variability with all longitudes poleward of 30 degrees latitude both in the Northern and Southern Hemisphere. These appear to be little connection to the tropical variability.

This result gives insight into the long-term global mean temperature variations. The North Pacific mode in the observations shows a rapid warming trend after 1985 and then persists until the present day. Similarly, the model result suggests that this kind of rapid warming of the North Pacific mode is possible in current coupled models. This abrupt warming in the model accompanies a significant warming of global mean surface temperatures and mean tropospheric temperature. The implication here is that global climate variations need to be interpreted within the context of North Pacific mode.

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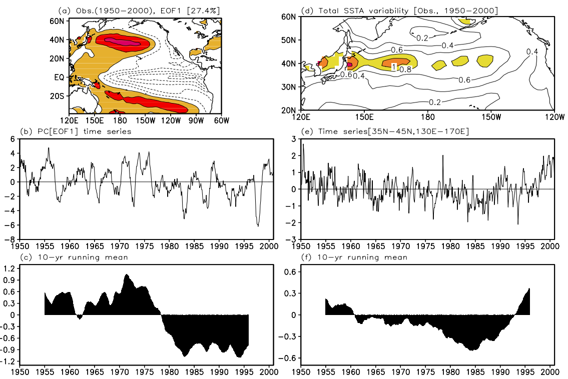

Figure 1. The first empirical orthogonal function (EOF) mode in the Pacific SST (a), the time series of the principal component (PC) (b) and that of a 10-year running mean (c) for the period of 1950-2000 in the observation. The first EOF of SST explains 27.4% of the total variance. Contour interval in (a) is 0.1°C. The total SSTA variance in the North Pacific for the period of 1950-2000 (d), the time series of SSTA averaged over 35°N-45°N, 130°E-170°E (e) and that of a 10-year running mean (f). Contour interval in (d) is 0.2°C^2 and Shading is for values above 0.8 °C^2.

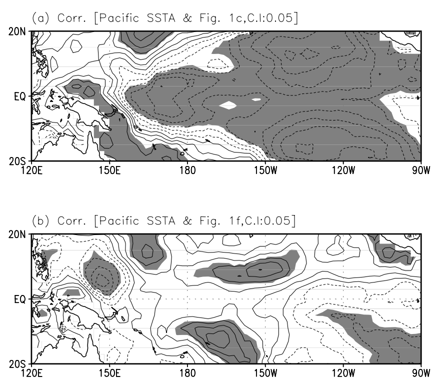

Figure 2. (a) The simultaneous correlation coefficients between the tropical SST and the PC time series of a 10-year mean of the first EOF in the Pacific. (b) is as in (a) except for the time series of a 10-yr running mean of North Pacific mode. Contour interval is 0.05 and shaded are for regions exceeding 95% significance.

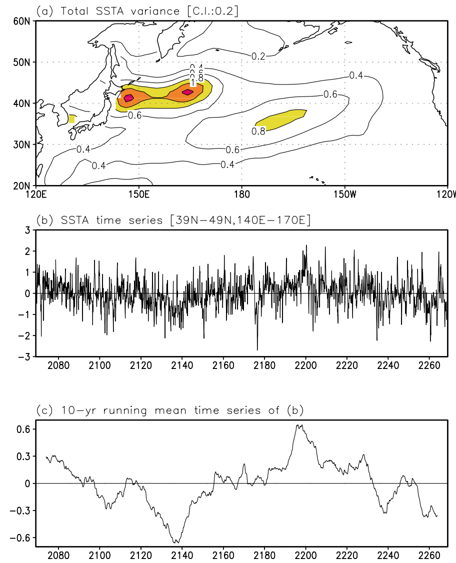

Figure 3. As in Figs. 1 d-f except for the SSTA variance simulated for the period of 200 years in the model over the region 39°N-49°N, 140°E-170°E. Contour interval in (a) is 0.2°C^2 and Shading is for values above 0.8°C^2.

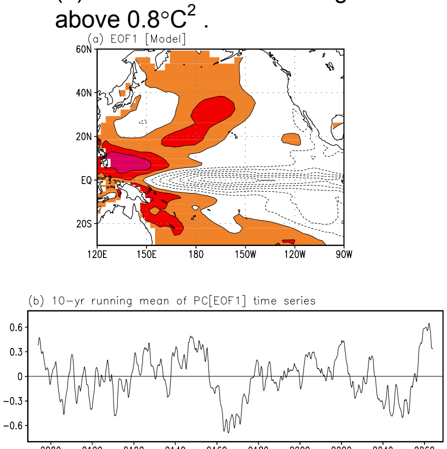

Figure 4. The first EOF mode for the Pacific SSTA simulated for the period of 200 years in the model (a) and a 10-yr runnning mean of PC time series (b).

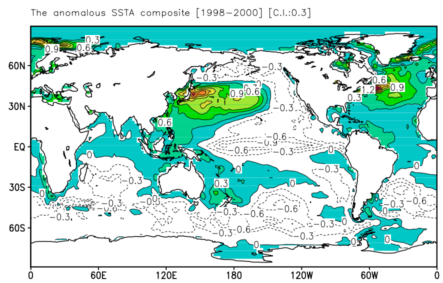

Figure 5. The anomalous SSTA averaged during the period of 1998-2000. Contour interval is 0.3°C and Shading is for positive.

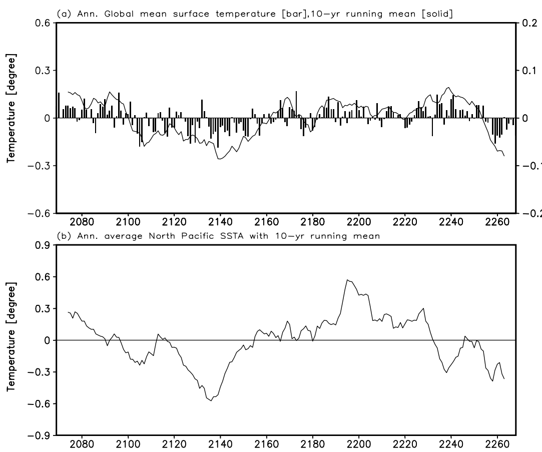

Figure 6. The time series of annual global surface temperature (bar) with a 10-yr running mean (solid) (a) and the 10-yr running mean of annual mean North Pacific SSTA variability (b) during the period of 200 years in the model. The averaged region of North Pacific SSTA variability in (b) is the same as in Fig. 3b.

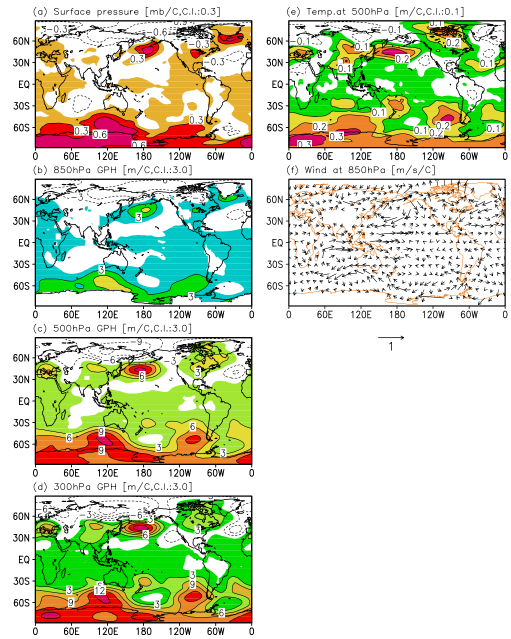

Figure 7. Linear regression coefficients plotted between model variables (i.e., surface pressure (a), geopotential heights at 850hPa (b), 500hPa (c), 300hPa (d), temperature at 500hPa (e), and wind anomalies at 850hPa (f)) and the time series of North Pacific mode shown in Fig. 3c. Shading is for positive.